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A NEW MODEL FOR IRON EMISSION LINES AND REBURSTS IN GAMMA-RAY BURST X-RAY AFTERGLOWS

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ABSTRACT

Recently, iron emission features have been observed in several X-ray afterglows of GRBs. It is found that the energy obtained from the illuminating continuum that produces the emission lines is much higher than that of the main burst. The observation of an SN-GRB association indicates that a fallback disk is formed after the supernova explosion. The disk is optically thick, advection-dominated, and dense. We suggest that delayed-injection energy after the initial main burst, much higher than the energy of the main burst, causes a reburst appearance in GRB afterglows, illuminates the region of the disk surface with $\tau \approx 1$ (τ is the optical depth for the Thomson scatter), and produces an iron emission line whose luminosity can be up to 10^{45} ergs s^{-1}. The duration of the iron line emission can be 10^4–10^5 s. This model can explain the appearance of rebursts and emission lines in GRB afterglows and the disappearance of the iron emission lines, and can also naturally solve the problem of the energy of the illuminating continuum being higher than that of the main burst. This scenario is different from the models previously put forward to explain the emission lines and can be tested by the *Swift* satellite.

Subject headings: accretion, accretion disks — gamma rays: bursts — line: profiles — supernovae: general

1. INTRODUCTION

Recently, evidence has been mounting that long-duration gamma-ray bursts (GRBs) are associated with rare types of supernova (SN) events, such as a failed supernova, hypernova, or collapsar (Woosley 1993; Paczyński 1998; MacFadyen & Woosley 1999; MacFadyen et al. 2001; Proga et al. 2003). In these models, the time between the SN explosion and the GRB is very short, nearly simultaneous. Another model, the "supranova model," was proposed by Vietri & Stella (1998), in which the SN explosion initially results in the formation of a comparatively massive, magnetized neutron star endowed with rapid rotation. This supramassive neutron star is envisioned to gradually lose rotational support through a pulsar-type wind until it eventually becomes unstable to gravitational collapse, leading to the formation of a black hole and the triggering of a GRB. In the supranova model, the time between the SN explosion and the GRB can range from several weeks to several years.

After the SN explosion, the fallback material will form a disk around the new central black hole in either the collapsar model or the supranova model, and this disk is advection-dominated, hot, and dense even after the GRBs (e.g., Chevalier 1989; Mineshige et al. 1997).

X-ray emission lines observed in X-ray afterglows of GRBs provide important clues for identifying the nature of the progenitors of long ($t \geq 2$ s) GRBs. The first marginal detection of an emission line was in the X-ray afterglow of GRB 970508 with *BeppoSAX* NFI (Piro et al. 1999). Later emission lines were also detected in the X-ray afterglows of GRB 970828 (Yoshida et al. 2001) with *ASCA*; GRB 991216 (Piro et al. 2000) and GRB 020813 (Butler et al. 2003) with *Chandra*; GRB 011211 (Reeves et al. 2002), GRB 001025A (Watson et al. 2002), and GRB 030227 (Watson et al. 2003) with *XMM-Newton*; and GRB 000214 (Antonelli et al. 2000) with *BeppoSAX*. The detailed properties of the X-ray emission features can be found in several papers (Lazzati 2002; Böttcher 2003; Gao & Wei 2004). The energy of the emission line found in the X-ray afterglows of GRB 970508, GRB 970828, GRB 991216, and GRB 000214 is roughly consistent with Fe Kα at the redshift of the hosts. This is adduced as evidence that the environment of the burst is heavily enriched in iron as the result of a recent SN explosion (e.g., Lazzati et al. 1999; Ghisellini et al. 1999). We would also observe the Fe line if the time delay were more than several months, such as in the supranova model (Vietri & Stella 1998).

The standard model of GRB afterglows assumes that relativistic material is decelerating on account of interaction with the surrounding medium, with a nearly impulsive injection energy. But perhaps the ejecta consist of many concentric shells moving at different speeds, and slow-moving material carries most of the system's energy. The delayed-injection energy could be more than that of the main burst. This is the proposed "refreshed shock" scenario. In this scenario, it is assumed that the source ejects a range of Lorentz factors with the mass $M(>\gamma) \propto \gamma^{-s}$ (Rees & Mészáros 1998; Sari & Mészáros 2000).

Reburst phenomena have been found in the afterglows of GRB 970508 (Piro et al. 1998) and GRB 970828 (Yoshida et al. 1999). It has been thought that delayed-injection energy that is higher than that of the initial burst caused the reburst appearance (Panaitescu et al. 1998; Kumar & Piran 2000; Sari & Mészáros 2000).

The energy contained in the illuminating continuum that is responsible for the line production is much higher than that of the collimated GRBs (Lazzati 2002; Ghisellini et al. 2002; Gao & Wei 2004). In this paper we suggest that the illuminating continuum that produces the emission line comes from the delayed-injection energy, which illuminates the fallback disk and produces the emission lines.

2. DELAYED ENERGY INJECTION AND THE Fe EMISSION LINE FEATURE IN X-RAY AFTERGLOWS

The reburst of emission during the afterglow has been reported in two GRBs, GRB 970508 (Piro et al. 1998) and GRB 970828 (Yoshida et al. 1999). At the same time, possible evidence for the existence of the Fe Kα line has also been found in GRB 970508 (Piro et al. 1999) and GRB 970828 (Yoshida et al. 1999). Delayed-energy injection (or the refreshed-shock model) can well explained the resurgent emission in these two GRBs (Panaitescu et al. 1998; Kumar & Piran 2000). The delayed-injection energy that is higher than the initial-fireball energy can produce the observed reburst in the afterglow about 0.5 days after the gamma-ray burst. Here we develop a model in which the delayed-injection energy illuminates the fallback disk around the central black hole and photoionizes the layer of the disk with $\tau = 1$, and in which iron line emission can be produced by the recombination process.

Consider an engine that emits both an initial impulsive energy input and a continuous luminosity, the latter varying as a power law in the emission time. The differential energy conservation relation in the observer's frame can be expressed as (Cohen & Piran 1999; Zhang & Mészáros 2001)

$$dE/dt_{\oplus} = L_0(t_{\oplus}/t_0)^q - k(E/t_{\oplus}), \quad t_{\oplus} > t_0. \tag{1}$$

The first term on the right-hand side, $L = L_0(t_{\oplus}/t_0)^q$, is the intrinsic luminosity of the refreshed shock; t_0 is the characteristic timescale for the formation of a self-similar solution, E and $t_{\oplus}$ denote the energy and time measured in the observer's frame, and q and k are dimensionless constants.

In the refreshed-shock scenario, following Rees & Mészáros (1998), Kumar & Piran (2000), and Sari & Mészáros (2000), one can obtain the relationship between the temporal index α and the spectral index β, where $F_{\nu} \propto t_{\oplus}^{\alpha}\nu^{\beta}$. For the X-ray afterglow, consider the forward shock in the slow-cooling regime (Sari et al. 1998), $\alpha = (1 - q/2)\beta + 1 + q$ (Zhang & Mészáros 2001). Since no spectral information was available for GRB 970508 in the first several days of the afterglow, in the calculation of Panaitescu et al. (1998), $s = 1.5$ is needed. For the forward shock in the slow-cooling regime in the refreshed model, $\alpha = -(6 - 6s - 24\beta)/2(7 + s)$ (Sari & Mészáros 2000; for a uniform-medium environment). So $\beta = (17\alpha - 3)/24$. In the X-ray afterglow observations of GRB 970508, the temporal index α changes from -1.1 (before the reburst) to +1.7 (at the beginning of the reburst), to -0.4 (during the reburst), and then to -2.2 (after the reburst) (Piro et al. 1999).

From the refreshed-shock scenario above, one can obtain the delayed-injection energy from $L \propto t_{\oplus}^{q}$, $q \sim -0.8$, and the energy ends after about 10^5 s. We assume that the delayed energy is isotropic, which is reasonable from the observations. On the observational side, Pedersen et al. (1998) have found that the optical light curve of the GRB 970508 afterglow can be explained in terms of an isotropic outflow. Radio observations of the GRB 991216 afterglow also showed there was an isotropically energetic fireball (10^{54} ergs; Frail et al. 2000). From the numerical work of Panaitescu et al. (1998), the energy injected into the GRB outflow is $E_{\rm inj} = 3E_0$. We call this the "Injection Energy," which is only a fraction of the whole delayed energy. The whole delayed energy is about $E_{\rm del} = \left(4\pi/\Omega_{\gamma}\right)E_{\rm inj}$ (Ω_{γ} is the solid angle of the GRB collimated jet). Again, luminosity varies as about $t_{\oplus}^{-0.8}$. At the beginning of the reburst, $t_i \sim 6 \times 10^4$ s, the Injection Energy is the same as that of the initial burst, $E_0 \sim 4 \times 10^{50}$ ergs (Bloom et al. 2003). After that time, the residual Injection Energy $2E_0$ is exhausted in about 10^5 s (Piro et al. 1999). We have

$$E = \int_{t_i}^{t_e} L_i \left(\frac{t}{t_i}\right)^{-0.8} dt, \tag{2}$$

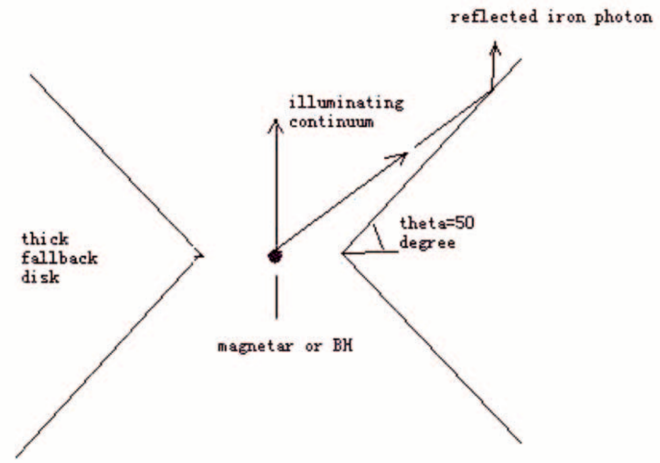

Fig. 1.—Cartoon picture of the geometry of the fallback disk. The central engine is a magnetar or black hole.

where t_i is the time at which the reburst appears, t_e is the time when the reburst ends, L_i is the luminosity at the time of reburst emergence, and E is the energy injected into the external medium. Again, after the emergence of the reburst the residual Injection Energy is about $2E_0$ and the time duration is about 10^5 s, and we can obtain that $L_i \sim 10^{46}$ ergs s^{-1}. From $L \propto t^{-0.8}$ and the energy E_0 that has been exhausted before the reburst, we get $L \sim 10^{47}$ ergs s^{-1} at $t \sim 3 \times 10^3$ s.

An advection-dominated disk can exist around a stellar black hole even after the GRB (Kohri & Mineshige 2002; Janiuk et al. 2004) (Fig. 1). For the collapsar model, the SN explodes at almost same time as the GRB, or about a minute to a few hours prior to the GRB, whereas for the supranova model, the time delay between the SN explosion and the GRB is perhaps several months or even longer. In this case almost all the fallback nickel has decayed to iron.

The evolution of the fallback disk around the black hole has been considered by, e.g., Meyer & Meyer-Hofmeister (1989), Cannizzo et al. (1990), and Mineshige et al. (1993, 1997). From the work of Mineshige et al. (1997), we can draw the accretion rate of the disk result from the fallback material. Since the radioactivity timescale is about 85 days for nickel decaying to iron, here we adopt the supranova model (Vietri & Stella 1998) and assume that the GRB takes place about 100 days after the SN explosion,

$$\dot{M} \sim 10^{25}\ \mathrm{g\ s^{-1}} \left(\frac{M_{\rm BH}}{3\ M_{\odot}}\right)\left(\frac{\Delta M}{0.1\ M_{\odot}}\right)\left(\frac{\alpha}{0.01}\right)\left(\frac{t}{100\ \mathrm{days}}\right)^{-1.35}, \tag{3}$$

where ΔM is the amount of fallback material of the disk and α is the viscosity parameter. We adopt the mass of the black hole as 3 $M_{\odot}$. The quantity ΔM has a large range for the different mechanisms of the SN explosion and evolution of the disk (e.g., Woosley 1993; Chevalier 1989). Here we adopt ΔM as 0.1 $M_{\odot}$.

By about 100 days after the SN explosion, the accretion rate would be decreasing to about 10^{-8} $M_{\odot}$ s^{-1}. At this time the radiation pressure is dominant in the disk (e.g., Mineshige et al. 1997). The relations T-Σ and $\dot{M}$-Σ are as follows (Kohri & Mineshige 2002):

$$T = 4.87 \times 10^1 \alpha^0 \Sigma^{1/4} r^{-1/2} M_{\rm BH}^{1/4}, \tag{4}$$

$$\Sigma = 3.3 \times 10^3 \dot{M} \alpha^{-1} r^{-1/2} M_{\rm BH}^{-1/2}. \tag{5}$$

The total mass of the disk is

$$\Delta M = \int_{R_{\rm in}}^{R_{\rm out}} 2\pi R \Sigma \, dR, \tag{6}$$

where $R_{\rm in}$ and $R_{\rm out}$ represent the innermost radius and the outermost radius, respectively. From equations (3), (5), and (6), and adopting $\Delta M = 0.1\ M_\odot$, we can obtain the radius of the outermost disk, $R_{\rm out} \sim 2\times10^{12}$ cm.

Thus we can get the results for the surface density Σ and temperature T at the outermost radius:

$$\Sigma = 4.5\times10^7 \text{ g cm}^{-2}\left(\frac{\dot{M}}{10^{25}\text{ g s}^{-1}}\right) \times \left(\frac{\alpha}{0.01}\right)^{-1}\left(\frac{r}{10^6 r_s}\right)^{-1/2}\left(\frac{M_{\rm BH}}{3\ M_\odot}\right)^{-1/2}, \tag{7}$$

$$T = 2\times10^6\text{ K}\left(\frac{r}{10^6 r_s}\right)^{-1/2}\left(\frac{M_{\rm BH}}{3\ M_\odot}\right)^{1/4}. \tag{8}$$

Then the average density of the disk at this time at the outermost radius $r = 10^6 r_s$ is

$$\rho = \frac{\Sigma}{2H} = 7.2\times10^{-5}\text{ g cm}^{-3}\left(\frac{\Sigma}{4.5\times10^7\text{ g cm}^{-2}}\right)^2 \times\left(\frac{T}{2\times10^6\text{ K}}\right)^{-4}\left(\frac{r}{10^6 r_s}\right)^{-3}\left(\frac{M}{3\ M_\odot}\right). \tag{9}$$

At the outermost radius, which is about $r = 10^6 r_s = 8.85\times10^{11}$ cm, the temperature T is about 2×10^6 K and the number density n is about 4×10^{19} cm^{-3} in the disk.

The ionization parameter is $\xi = L_{\rm ill}/nR^2 = 2.5\times10^3[L_{\rm ill}/(10^{47}\text{ ergs s}^{-1})][n/(4\times10^{19})]^{-1}[R/(10^{12}\text{ cm})]^{-2}$. At this ionization parameter, iron emission is very efficient (Lazzati et al. 2002). The recombination time for hydrogenic iron in the outer disk photoionized by the nonthermal delayed energy is (Lazzati et al. 1999)

$$t_{\rm rec} = 1.5\times10^{-8}T_8^{1/2}n_{17}^{-1}\text{ s}. \tag{10}$$

The temperature parameterization used here is consistent with the range expected from photoionization equilibrium (Lazzati et al. 1999).

The optical depth at outer radius $r = 10^{12}$ cm is optically thick: $\tau_{\rm T} = 2nH\sigma_{\rm T} \sim 10^7$. So the number of Fe nuclei in the layer of the disk with $\tau = 1$ is $N_{\rm Fe} \sim \chi_{\rm Fe}M/(\tau_{\rm T}56m_p) \sim 10^{47}\chi_{\rm Fe}$ ($\chi_{\rm Fe}$ is the iron mass fraction of the disk). The Fe line luminosity is $[N_{\rm Fe}(8\text{ keV})/t_{\rm rec}](1+z)^{-1}$, or

$$L_{\rm Fe} \sim \chi_{\rm Fe}10^{47}(1+z)^{-1}\text{ ergs s}^{-1}. \tag{11}$$

For SN 1987A, $\chi_{\rm Fe}$ can be about 2% when all the nickel has decayed to iron (Chevalier 1989). So the luminosity of iron line can be obtained: $L_{\rm Fe} \sim 2\times10^{45}(1+z)^{-1}$ ergs s^{-1}.

After the emergence of the reburst, luminosity decays from about 10^{46} ergs s^{-1} at the rate of $t^{-0.8}$. So the luminosity of the iron line should decrease and disappear during the reburst, consistent with observations of the iron line (Piro et al. 1999).

Note that we assume that the delayed energy is almost isotropic. The energy obtained by the disk is $E_{\rm disk} = (\Omega_d/4\pi)E_{\rm del}$; Ω_d is the solid angle subtended by the fallback disk as observed at the location of the central engine. For the advection disk, $H/R \approx 0.77$ (Narayan et al. 2001). We get $E_d \approx 0.37E_{\rm del}$. For GRB 970508, the open half-angle of the GRB collimated jet is $16\overset{\circ}{.}7$ (Frail et al. 2001). So the energy obtained by the disk is $E_d \sim 60E_0$. Even if only 10% of the energy was reflected by the disk (e.g., Zycki et al. 1994), this gives about $3E_0$ reflected by one surface of the disk, which is sufficient for the line emission production.

3. DISCUSSION AND CONCLUSIONS

We have found that the energy contained in the illuminating continuum that is responsible for line production is much higher than that of the collimated main GRBs. In our model the delayed-injection energy, higher than that of the collimated GRBs, illuminates the fallback disk that is formed after the SN explosion, photoionizes the disk region of $\tau = 1$, and then produces the observed iron line feature.

In our model the delayed energy comes from the central engine, which can be the magnetic energy from the declining magnetic field of the superpulsar (Rees & Mészáros 2000) or the magnetic dipole radiation of the magnetar (Dai & Lu 1998). It could be primarily in a magnetically driven relativistic wind (which would be super-Eddington). The magnetized wind would develop a shock before encountering the disk. The nonthermal electrons would be accelerated behind the shock in the outflow material. The shock-accelerated electrons could cool promptly and would yield a power-law X-ray continuum. This is similar to what has been proposed by Rees & Mészáros (2000). This X-ray continuum illuminates the fallback disk and produces the iron line. The surface of the disk can be accelerated outward by this super-Eddington flux of the illuminating continuum (e.g., Vietri et al. 2001), so usually an outward velocity can be seen in the lines (e.g., Reeves et al. 2002). In our model, the delayed energy emission and the GRBs could come from different physical processes. The delayed energy could be from magnetic wind of the magnetar, so the energy emission would be almost isotropic. However, from the observation of the GRBs, the GRB prompt emission should be intrinsically collimated. So there should exist a transition from a collimated to an uncollimated energy release in the engine.

The Injection Energy must be higher than that of the initial main burst in order for the effect to be observed in the GRB afterglows (Cohen & Piran 1999; Zhang & Mészáros 2001). For GRB 970508, at $t \sim 3\times10^3$ s after the GRB, the delayed illuminating continuum decays to 10^{47} ergs s^{-1}, the ionized iron ion recombines, the Fe line appears, and the line luminosity is about 10^{44}–10^{45} ergs s^{-1}. At the time $t \sim 6\times10^4$ s, the reburst emerges. And after that time, the luminosity of the delayed illuminating continuum decays to less than 10^{46} ergs s^{-1} and the iron line would decrease and disappear. The duration of the Fe line $t_d \sim 10^4$–10^5 s, longer than the cooling time of thermal disk $t_{\rm cool} \sim 10^{-4}n_{19}^{-1}$ s. All the above are consistent with the observations of the Fe line in the GRB 970508 X-ray afterglow.

The reburst phenomenon has not been observed in the GRB 991216 afterglow. An explanation for this could be that the Injection Energy was as much as or less than that of the main burst, or that the reburst was missed in the observation even though it happened. In the former case, the line duration should be 10^4 s or less, consistent with what has been observed, adopting the energy of the main burst as $E \sim 10^{51}$ ergs (Bloom et al. 2003).

The above scenario is based on the supranova model, in which the time delay between the SN explosion and the GRBs can be several months or even longer. Our model supports the supranova model because it must have enough time to let nickel decay to iron (about $10^{-3}\ M_\odot$ Fe in the disk). In our model we assume that the time between the SN explosion and the GRB is about 100 days, so the fallback disk that we consider has evolved for about 100 days after the SN explosion. In this case, the lines and the SN bump cannot be seen in the same events.

In our model, the disk was in place before the GRB occurred, so it may produce a high level of pre-GRB activity of the source.

Different values of the ionization parameter, ξ, could produce the different reflection spectra. When $\xi \sim 10^2$, the spectra will show luminous lines from light metals and a depressed Kα iron line; when $10^3 < \xi < 10^5$, a luminous iron line will be observed in the spectra (Lazzati et al. 2002). In our model the fallback disk with different properties, such as a different number density of the electrons in the disk surface and the outermost radius, will have a different ionization parameter. In this paper, $\xi \sim 2.5 \times 10^3$, so the luminous Kα iron line can be observed in the spectra.

Vietri et al. (1999) have suggested a thermal model in which a relativistic fireball associated with the GRB might hit the pre-GRB supernova remnant within $\sim 10^3$ s and heat the ejecta to $T \sim 10^7 - 10^8$ K. At such temperatures the plasma emission shows thermal bremsstrahlung emission as well as iron line emission. In their model the thermal bremsstrahlung and recombination continuum from the thermal disk can account for the reburst observed in GRB 970508 and GRB 970828, while in our model the delayed-injection energy from the central engine after the main burst, more than the energy of the main burst, accounts for the reburst and produces the iron line emission.

Our model is also different from the decaying magnetar model, in which Rees & Mészáros (2000) suggested that iron line could be attributed to the interaction of a continuing but decaying postburst relativistic outflow from the central engine with the progenitor stellar envelope at distances of less than a light-hour. In their model bumps should be found in less than several hours after the GRBs (Gao & Wei 2004).

In conclusion, we suggest that the delayed-injection energy that causes the reburst in the GRB afterglow illuminates the fallback disk that is formed after the supernova explosion, photoionizes the fallback disk, and then produces the iron line feature. This scenario can well explain the production of the reburst and the emission lines and can be tested by the observations of the *Swift* satellite in the near future.

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